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Glacier mapping: a review with special reference to the Indian Himalayas

Rakesh Bhambri[1]* and Tobias Bolch[2]

[1]Guru Nanak Khalsa College, Karnal - 132001, Haryana, India
[2]Institut für Kartographie, Technische Universität Dresden, 01069 Dresden, Germany

Abstract: This paper deals with the development of glacier mapping and glacier fluctuations since the mid-nineteenth century, with special reference to the Indian Himalayas, and the contributions of the Survey of India and the Geological Survey of India. In addition, it presents a review of the limitations and challenges relating to: the mapping of clean-ice and debris-covered glaciers; the comparison of different data sets; and the measurement of glacier volume changes based on multitemporal digital elevation models. Possible solutions are discussed, and the emerging areas of glacier mapping research and applications for the Indian Himalayas are highlighted.

Key words: ASTER, digital elevation model, glacier fluctuation, glacier mapping, Indian Himalayas, remote sensing.

I Introduction

The principal goal of glacier mapping is to represent the spatial morphology of glacier terrain features on maps. Glacier maps are well established as valuable records of glacio-geomorphic features in particular time periods (Ashwell, 1982). Moreover, using recent geo-informatics techniques, it is possible to prepare 2D/3D digital maps for visualization of glacial terrain (Buckley *et al*., 2004; Bolch, 2008). Glaciologists can also use these techniques to obtain information about glacier variability (Hall *et al*., 2003), estimate mass balance (Østrem and Haakensen, 1999; Andreassen, 1999), infer the morphometric status of glaciated regions (Sangwar *et al*., 2004), calculate changes in ice volume (Surazakov and Aizen, 2006; Bauder *et al*., 2007; Bolch *et al*., 2008), and estimate the position of the equilibrium line (Leonard and Fountain, 2003). However, all such uses are fundamentally governed by the accuracy and availability of the original map resource.

The Himalayas comprise one of the largest collections of glaciers outside the polar regions, with a glacier coverage of ~33,000 km^2 (Dyurgerov and Meier, 1997) and a

*Author for correspondence. Present address: Soil and Crop management division, Central Soil Salinity Research Institute, Kachawa Road, Karnal - 132001, India.
Email: rakeshbhambri@gmail.com

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total number of 5243 glaciers (Kaul, 1999; Hasnain, 1999). The Himalayas form a natural barrier between the southern Indian Peninsula and mainland Asia, extending 2500 km from Pamir Knot in the west to Arunachal Pradesh in the east with the three parallel ranges, the Himadri, Himachal and Shivaliks. Himalayan glaciers in the Indian subcontinent are broadly divided into the three river basins, namely the Indus, Ganga and Brahmaputra (Figure 1). The Indus basin has the largest number of glaciers (~3500), whereas the Ganga and Brahmaputra basins contain about 1000 and 660 glaciers, respectively (Kaul, 1999; Hasnain, 1999). Himalayan glaciers are an important source of fresh water for northern Indian rivers and water reservoirs (Kumar *et al*., 2005). The inventory of Himalayan glaciers indicates that many Himalayan glaciers are receding at an alarming rate (Kulkarni *et al*., 2005; 2007). Due to the rapid recession of glaciers, a number of catastrophic effects such as glacial lake outburst floods (WWF, 2005; Mool *et al*., 2007), water scarcity in the upper Himalayan villages and adverse effects on the flow of Himalayan rivers have been reported (Kulkarni *et al*., 2002; 2007). For water resources planning and management in northern India, it is essential, therefore, to study and monitor the Himalayan glaciers precisely. Advanced remote sensing and GIS techniques offer abundant potential for mapping and monitoring the glaciers in

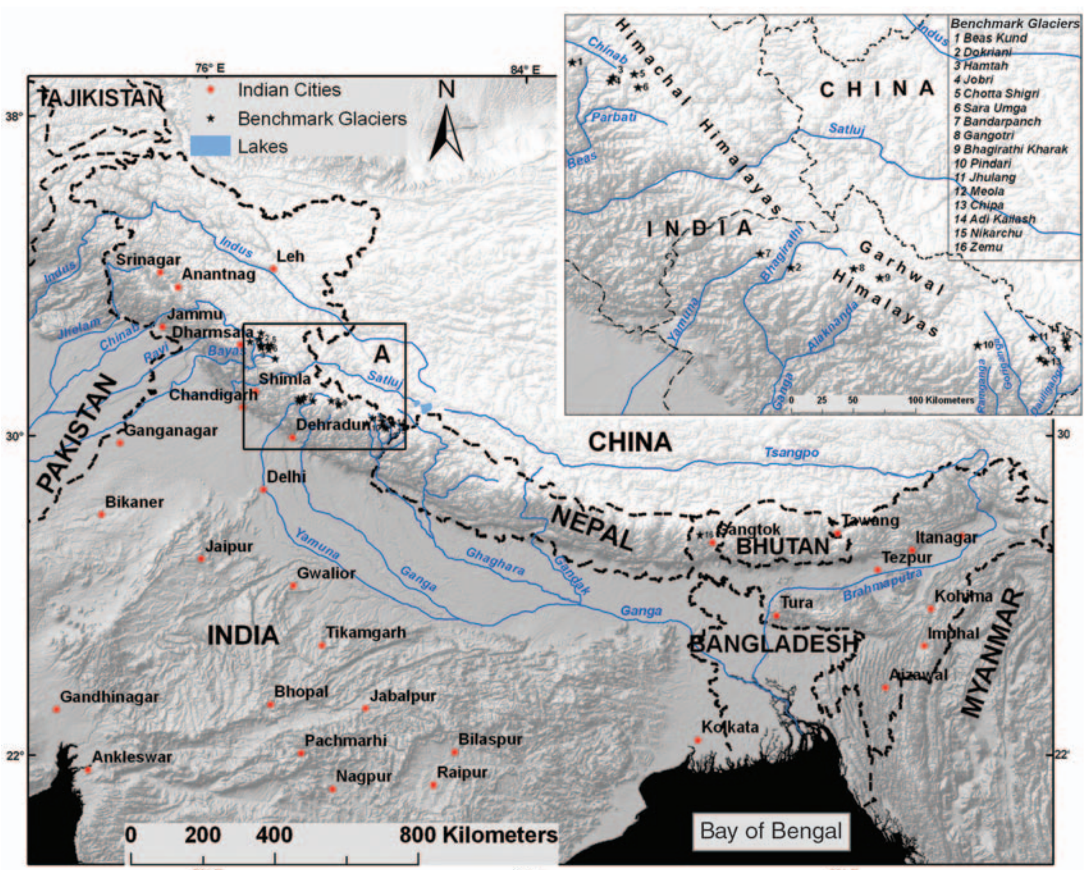

Figure 1 Overview of the Himalayas with the benchmark glaciers in the Indian Himalayas (political boundaries are only tentative)

extensive high and remote mountain areas, whereas conducting a survey based on conventional methods demands a great deal of time and capital and involves enormous risks.

This paper presents a review of glacier mapping in the Indian Himalayas since the mid-nineteenth century. It also highlights the advantages and problems of remote-sensing-based glacier mapping, and sheds light on the emerging areas of national as well as international glacier research and applications, with special reference to the Indian Himalayas. In addition, overviews of the current knowledge on the fluctuations of the Indian Himalayas are also presented.

II Topographic glacier mapping since the mid-nineteenth century

During the early seventeenth century, glacier boundaries and surrounding features were represented as rough sketches. However, the first claim on the making of an accurate large-scale map for glaciological purposes (Venediger Group, Alps) was made by Eduard Richter, the first chairman of the German and Austrian Alpine Club (Brunner, 1987). The history and development of glacier mapping in other countries is well documented by Williams and Ferrigno (1988–2008), yet to this day there is still no such documentation on the Indian Himalayan glaciers. However, more recently, Raina and Srivastava (2008) presented a glacier inventory and historical documentation of the glaciological studies in India, with details for a few selected glaciers. The Survey of India (SOI) is the primary agency of India involved in surveying the Himalayan mountain region since its establishment in 1767. The records of many surveys, especially Colonel Godwin-Austen's plane-table surveys of the Mustakh range (Godwin-Austen, 1864), Conway's journey to the Hisper Glacier in 1892 (Conway, 1893), various expeditions of Mr and Mrs Visser, and the Shaksgam expedition by Mason and Shipton (Mason, 1927a; Shipton *et al.*, 1938) have made notable contributions to glacier mapping of the Himalayas. All of these surveys and expeditions contributed significant information for tracking the following:

(1) mapping of unexplored valleys, peaks, passes and glacier terrain of the Himalayas;
(2) correcting maps of the earlier Himalayan terrain through improved scientific instruments and advanced techniques;
(3) recognizing a variety of changes within the glacier on the basis of previous glacier snout maps.

In the early nineteenth century, the mapping of Himalayan terrain was carried out using plane-table surveying and heavy theodolites. Purdon (1861) and Godwin-Austen (1864) began the survey and mapping of Himalayan glaciers. The Geological Survey of India (GSI) initiated the monitoring of secular movements of the principal Himalayan glaciers as part of the programme of the Commission International des Glaciers during 1906–1908. Initially, a total of 12 glaciers were studied by the Geological Survey of India (GSI) (Holland, 1907). Plane-table glacier sketches were made for all the glaciers, showing the snout and other geomorphic features. In some cases, cairns were also constructed for further reference.

Workman (1903) found, during an expedition to Baltistan, that glaciers had not always been delineated correctly during the great trigonmetrical survey by Godwin-Austen (1861). Similar conclusions were reached by Longstaff (1908; 1911) regarding the Garhwal Himalayas and Eastern Karakoram. Longstaff (1910a) also surveyed the Siachen Glacier in June 1909, and discovered that Siachen was the largest glacier (44 miles) in the Himalayan range. Visser (1926) reported that the delineation of Malangutti Glacier was incorrect on the 1915 Survey Map. Moreover, Mason (1928) established that Indira Col was shown on Workman's' map from his Shaksgam Valley expedition approximately one mile too far northward,

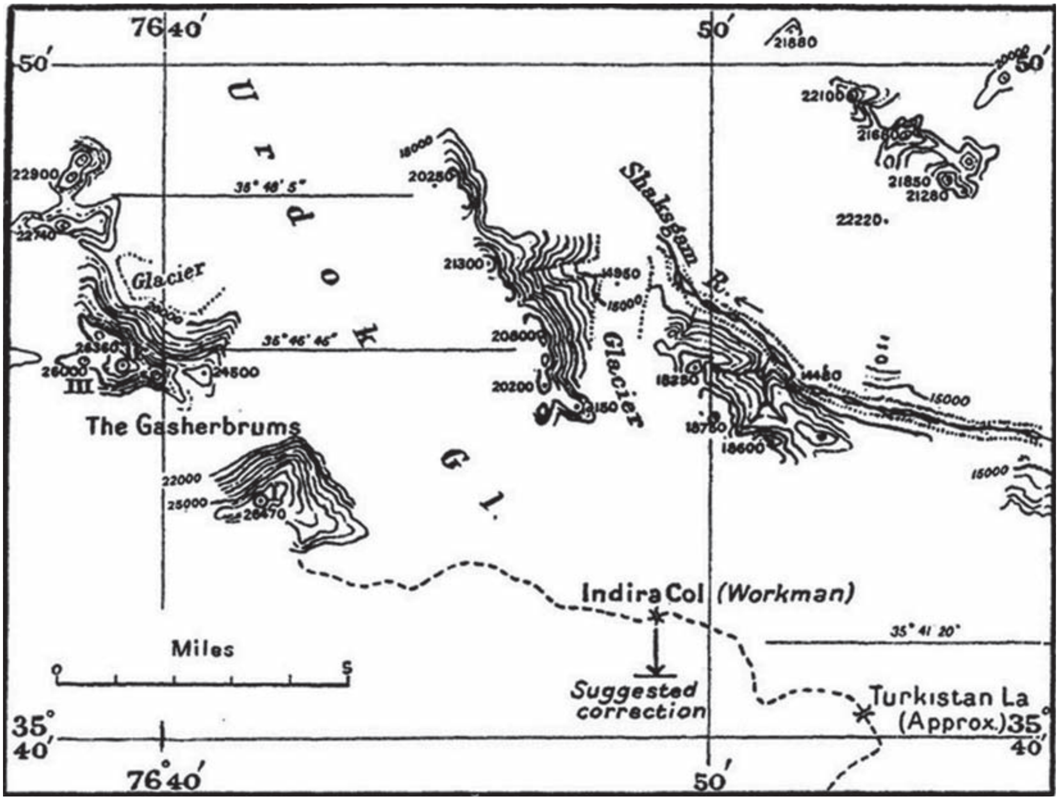

Figure 2 Part of the map illustrating Major Mason's Stereographic Survey of the Shaksgam (October 1927)

Source: Mason (1928). Map published with the permission of the Royal Geographic Society (with IBG).

and he subsequently corrected this (Figure 2). P. Bauer surveyed the Zemu Glacier by terrestrial photogrammetry and prepared a large-scale glacier map (Finsterwalder, 1935). Finsterwalder and Pillewizer (1937) used a stereo-photogrammetry method for the investigation of ice-flowing movement of the Rakhiot Glacier.

Shortcomings in the representation of glacier and geomorphic features on the Survey of India maps were first pointed out by Mason (1929) in his review article. Mason concluded that there is a need to first train surveyors in recognizing the morphology of glaciers and typical glacier features and their movements, before one can expect the glaciers to be surveyed and drawn correctly. In the review article, Mason proposed colour schemes and guidelines for the representation of glacio-geomorphic features on SOI maps (Table 1) to be replaced by voids in black and white and colour-hachured maps (Figure 3). Historically, glacio-geomorphic features such as ice caps could not be distinguished from rocky summits. Also, sometimes the words 'Glacier' or 'Snow-bed' were written across the blank space on SOI maps. Other details of the cartographic representation are described in Table 2.

Auden (1937) was the first geologist to systematically map the snout and geomorphic features of the Gangotri Glacier using a plane-table survey at a scale of 1:4800. J.C. Ross cross-checked the plane-table map in the field.

Table 1 Colour schemes for glacier-geomorphic features on Survey of India maps (from Mason, 1929)

Features	Plane table	Map	Remarks
Limits of all areas of permanent glaciations, whether glacier or neve, and all ice features	Yellow-green	Blue	No tint. The limits of the glacier will be shown by a fine line of dots.
Water features whether on or off ice	Violet-blue	Blue	
Live or barren dead moraines, lateral, medial, or terminal; scree, rockfalls and fans	Black	Black	Care should be taken to avoid the appearance of sand. The rocks comprising moraine are all sizes; the dots should be, too.
Dead moraines if under vegetation (grass, scrub or trees)	Burnt Sienna	Brown	
Contours across glaciers and neve, including those across live moraine	Yellow-green	Blue	
Contour values pertaining to the above:			The contour values may be either alongside or breaking the contour line, whichever is most suitable.
(a) across ice and snow	Yellow-green	Blue	
(b) across moraine	Black	Black	
Contours across hill slopes below the snowline, across dead moraines, scree, fans, etc	Burnt Sienna	Brown	Brown contours should never be shown above the snow-line. Bare ground above this line must be cliff, and should be shown by the cliff symbol
Cliffs above or below the snowline	Burnt Sienna	Brown	
Paths, tracks, routes, huts	Red	Red	
Passes and names	Black	Black	

This map was reproduced at 1:9600 scale by Auden (1937) and formed the basis of more than a dozen studies on the recession of the Gangotri Glacier conducted by the GSI. Several scientists from the GSI resurveyed the Gangotri Glacier and marked the position of the snout on Auden's plane-table map as well as cairns on the ground (eg, Jangpangi, 1958; Tiwari, 1972). A large number of Indian and British surveyors thus used contemporary techniques and instruments for surveying unexplored Himalayan ranges and paved the way for future generations of explorers in mapping the Himalayan peaks and glaciated terrain in extreme climatic and high-altitude conditions.

In the 1960s, the Survey of India published topographical maps of Himalayan glacier terrain on the basis of aerial photographs with limited fieldwork at a scale of 1:50,000. To date, five topographical maps, nos. 53E/5, 9, 10, 13 and 14, are available in open series maps (OCM) which cover a small segment of Indian Himalayan glaciers. Other topographic maps which cover the remaining, larger segment of Indian glaciers are defence series maps (DSM) and are restricted (Survey of India, 2005). Since the beginning of the twentieth century, GSI have mapped several glacier snouts and surrounding glacio-geomorphic features such as Gangotri, Pindari, Milam, Shankulpa, Gor Garang, Triloknath, Poting and many others for monitoring glacier recession and advance using plane-table mapping. The Survey of India parties, along with GSI, visited several Himalayan glaciers such as Gara Glacier in 1973, Neh-Nar Glacier in 1978 and Dunagiri in 1987, and then mapped the glacier snout area

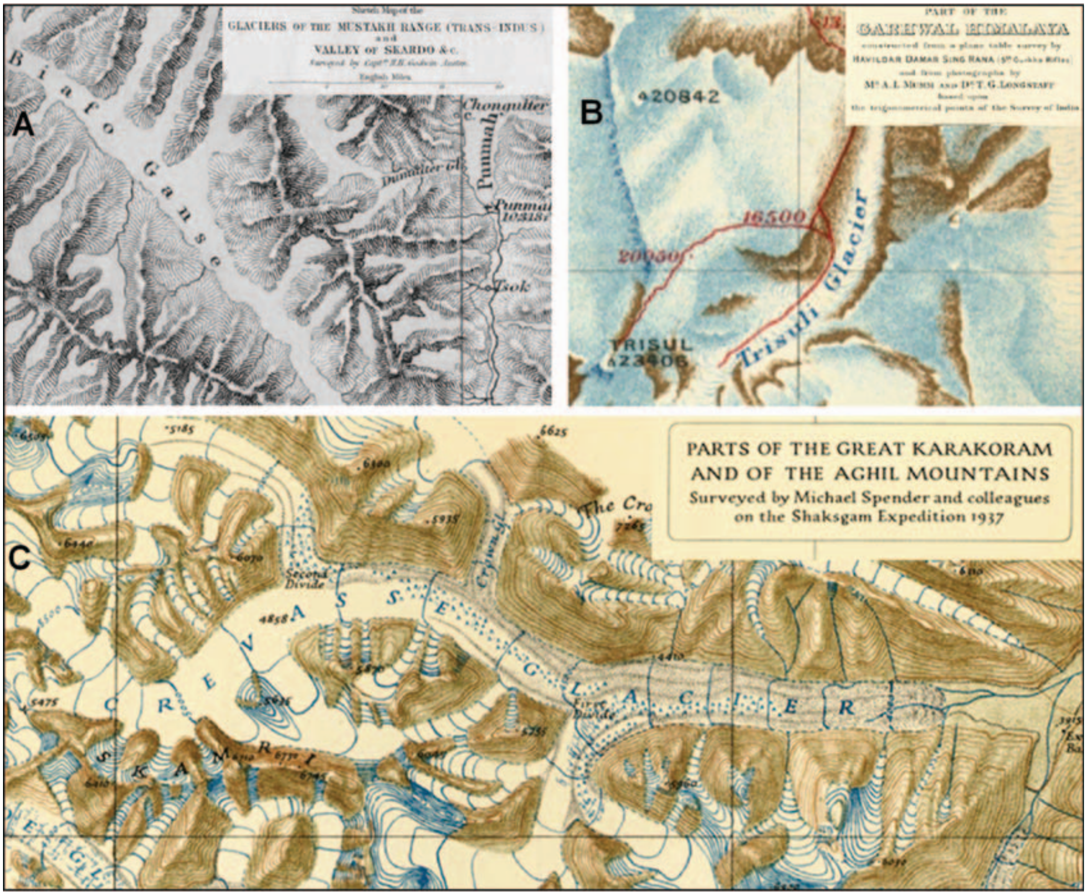

Figure 3 Rearrangement of the topographic glacier map of the Himalayas for visualization. (A) Black-and-white plane-table survey map without contours by Godwin-Austen (1864). (B) Coloured plane-table survey map without contours by Longstaff (1908). (C) Coloured stereo-photography survey map with contours by Shipton *et al*. (1938). Maps published with the permission of the Royal Geographic Society (with IBG)

at 1:5000 scale (Srivastava, 2001). Agarwal (1989) mapped the Neh-Nar Glacier with a contour interval of 10 m using the terrestrial photogrammetric technique. A literature review suggests that only three large-scale topographic glacier maps have been prepared by the Survey of India since India obtained its independence in 1947. One of the maps was prepared by SOI for Meru bamak at 1:5000, Garhwal Himalayas, in 1977 (Chitranshi *et al*., 2004). In 1984 and 1995, SOI prepared maps at a scale of 1:10,000 for Dokriani and Chotta Shigri Glaciers, respectively (Roy, 2001; Dobhal *et al*., 2004). These maps were prepared by the SOI during Inter-departmental expeditions. Chaujar (1989) published the first geomorphological map of Chotta Shigri Glacier at a scale of 1:10,000. In contrast, more than a dozen glacier maps had been produced at a scale of 1:10,000 by the end of the nineteenth century, with the development of cartography as an independent discipline (Brunner, 1987). It is noteworthy that in Norway alone as many as 24

Table 2 Details of glacier mapping during selected expeditions in the Himalayas

Authors	Location	Surveyors	Instrument used in expedition	Brief description
Godwin-Austen (1864)	Mustakh Range	Godwin-Austen and survey party from Survey of India	Plane table	This study is the first survey of Mustakh range and mapped Chogo Loombah, Masherbrum, Bande Loombah, Biafo, Punmah, Sobfindi and Mustakh Glaciers on trigonometrical survey map
Fanny Bullock Workman (1906)	Baltistan	Mr Hewett of London, as topographer, Dr William Hunter Workman and Mrs Fanny Bullock Workman	Theodolite	This study mapped Hoh Lumba and Sosbon Glaciers at 1:250,000 scale without contours
Longstaff (1908)	Garhwal Himalayas	Subhadar Karbir Burathoki, Havildar Damar Singh Rana, and seven riflemen from 5th Gurkha Rifles	Plane table, Hypsometers and Watkins mountain aneroid for metrological data collection	This study mapped more than a dozen glaciers, such as Bagini, Trisuli, Betatoli, kamet, Dunagiri, Juma, Ravikana, Banke, Bhyunder, Khaiam, Bidum, Abijurun, Sukeram, and Maiktoli, using plane-table and trigonometrical points from Survey of India at 1:250,000 scale
Longstaff (1910b)	Eastern Karakoram	Longstaff	Plane table, theodolite, clinometers	Topographic map was prepared showing Rgyong, Bawoni, Beltus, Chulung, Korisa, and many other glaciers at 1:500,000 scale without contours
Filippo de Filippi (1911)	Karakoram Himalayas	Lieutenant Negrotto	Paganini's photogrammetry supplemented by theodolite Mensuration, mercurial Fortin barometers, aneroids, and hypsometers	In this study, Godwin-Austen Glacier and Baltoro Glacier mapped using intersection photogrammetric method at 1:125,000 scale
Mason (1914)	Pamir mountain region	Mason	Thompson phototheodolite	Mason introduced stereo-photography method devised by Captain Vivian Thompson, R.E., in Pamir mountain region
Mason (1927a)	Shaksgam	Khan Sahib Afraz Gul Khan	Wild phototheodolite	Mason prepared a topographic map of Kyagar Glacier at 1:50,000 scale using stereoscopic survey with contour interval of 250 ft

(*Continued*)

Table 2 *Continued*

Authors	Location	Surveyors	Instrument used in expedition	Brief description
Mason (1927b)	Shaksgam Valley and Aghil Range	Khan Sahib Afraz Gul Khan	Wild phototheodolite	Mason prepared a topographic map of Shaksgam Valley and Aghil Range at 1:250,000 scale with contour interval of 500 ft. In this expedition, Mason successfully demonstrated contouring of K2 Glacier terrain at a distance of 42 miles by terrestrial stereo-photogrammetry
Visser (1926)	West of Hunza river, Karakoram	Khan Afraz Gul Khan from Survey of India	Plane table	This study mapped Hispar and its tributary glaciers on a scale of 1 inch to 1 mile
Visser (1934)	Karakoram and Turkistan	Khan Afraz Gul Khan, Muhammad Akram	Plane table	Topographic map was prepared at 1:500,000 scale with 1000 ft contour interval
Shipton *et al*. (1938)	Shaksgam	Eric Shipton, Michael Spender, J.B. Auden	Watts-Leica phototheodolite, subtense-bar and plane table, telescopic alidade, level, plumb-bob, box-compass, slide rule	This study mapped more than a dozen glaciers such as Baltoro, Sarpo Laggo, Nobande Sobande, Panmah, Biafo, Trango, Uli Biaho, Braldu, Choktoi, Cornice, Hoh Lungma, Sosbon, Virjerab, and Hispar, using plane table and phototheodolite at 1:250,000 scale
Mott (1950)	Karakoram Himalayas	Shipton, Fazal Ellahi and Inayat Khan from Survey of India	Zeiss TAL phototheodolite	The Panmah, Choktoi and Nobande Sobande Glaciers were surveyed by Shipton, using the Zeiss TAL photo-theodolite; he introduced in India the single picture method of photographic mapping during his survey

glaciers were mapped more than once on a large scale between 1952 and 1996 (Østrem and Haakansen, 1999).

III Glacier mapping using remote sensing and GIS

1 Manual delineation

As discussed earlier, topographic glacial mapping based on plane-table and terrestrial photogrammetry required an enormous human and time investment. In comparison, remote sensing data facilitates rapid glacier mapping as fieldwork is only necessary for ground truthing and to obtain ground control points. Initial glacier inventory studies using remote sensing, such as by Williams (1986) and Hall *et al*. (1992), started in Iceland and Austria, respectively, with the manual digitization of glacier boundaries on standard false colour composites (FCC) of Landsat MSS and TM images. This method is time-consuming for larger areas, and its accuracy depends on the efficiency of identification and recognition of glacier terrain features on satellite imageries.

In India, almost all the glacier inventories based on satellite imageries have been carried out by manual delineation (Table 3). These studies used FCC of coarse-resolution satellite data (eg, MSS and LISS I) to high-resolution data (eg, LISS IV and PAN), and SOI topographic maps whose scale ranged from 1:250,000 to 1:50,000. Few inventories based on remote sensing and topographical maps included cartographic errors in their studies. In the early 1990s, the Space Application Centre (SAC) completed a glacier inventory programme for the entire Indian Himalayas at a scale of 1:250,000 (Bahuguna, 2008).

2 Automated glacier mapping

Automated mapping of glaciers involves image processing techniques on multispectral data such as simple band mathematics and

Table 3 Details of satellite data used in glacier mapping studies of the Indian Himalayas

Authors	Location	Satellite data/map and spatial resolution/scale	Quantification of cartographic errors	Brief description
Dhanju and Buch (1989)	Parbati – Spiti basin	Landsat TM-30 m	Not mentioned	This study used FCC of bands 2, 3 and 4 for the manual delineation of glaciers
Kulkarni (1991)	Himachal Himalayas	Landsat TM-30 m IRS LISS-II-36.5 m	Not mentioned	This study manually delineated 125 glaciers using FCC (bands 2, 3 and 4) of satellite image
Kulkarni *et al.* (1999)	Satluj basin	Landsat TM-30 m IRS LISS-II-36.5 m	Not mentioned	For the additional altitude information this study used SOI topographical maps. In this inventory, the Himalayan Glacier Information System (HGIS) was developed using dBase III program
Dobhal and Kumar (1996)	Himachal Himalayas	SOI topographical maps (1:250,000) Landsat TM-30 m	Not mentioned	This study mapped glaciers of the entire Himachal Himalayas except the NE part of the Spiti basin, which was omitted due to strategic importance and restricted nature
Kulkarni and Suja (2003)	Baspa basin	IRS LISS III-23.5 m	Not mentioned	This study mapped 19 out of 30 glaciers in Baspa basin. In this study, authors did not include hanging glaciers, permanent snowfields and rock glaciers

(*Continued*)

Table 3 *Continued*

Authors	Location	Satellite data/map and spatial resolution/scale	Quantification of cartographic errors	Brief description
Dobhal *et al*. (2004)	Dokriani Glacier	SOI topographical glacial map (1:10,000)	Not mentioned	This study estimated ice volume change and recession rate of the Dokriani Glacier
Kulkarni *et al*. (2005)	Parbati basin	SOI topographical map (1:50,000) Landsat TM-30 m IRS LISS-III-23.5 m IRS PAN-5.8 m	Not mentioned	This study manually delineated Parbati Glacier on various temporal satellite images
Kulkarni *et al*. (2007)	Himachal Himalayas	SOI topographical map (1:50,000) Landsat TM-30 m IRS LISS-III-23.5 m IRS LISS-IV-5 m	Not mentioned	This study manually delineated 466 glaciers of Chenab, Parbati and Baspa basin of the Himachal area
Berthier *et al*. (2007)	Spiti/Lahaul region	ASTER-15 m	±2 pixels (30 m)	This study used manually delineated glacier boundaries for mass balance estimation
Krishna (2005)	Tista basin, Sikkim Himalayas	LISSI, LISSII and LISSIII satellite data of IRS	Not mentioned	This study used automatic NDSI technique for mapping of snowcover
Philip and Ravindran (1998)	Upper Bhagirathi basin	Landsat TM-30 m	Not mentioned	This study mapped landforms of Gangotri Glacier using Landsat TM and concluded that FCC of bands 4, 5 and 7 are suitable for glacier mapping

classification. Automated mapping of snow and ice is based on the fact that snow exhibits high reflectance in the visible and near-infrared region (VIS and NIR) as compared to short-wave infrared (SWIR) region of the solar spectrum. Bayr *et al*. (1994) and Rott (1994) proposed thresholds of a ratio image of TM-4 to TM-5 (NIR/SWIR) and TM-3 to TM-5 (RED/SWIR) ratio bands to delineate glacier ice area. Paul (2001) evaluated both ratio image techniques and concluded that the TM-4 to TM-5 ratio technique is the more appropriate for clean-ice glacier mapping. The ratio RED/SWIR performs better in areas with dark shadow and thin debris cover (Paul and Kääb, 2005; Andreassen *et al*., 2008). A number of inventories used simple and robust ratio methods (Paul *et al*., 2001; Bolch, 2007; Andreassen *et al*., 2008). Hall *et al*. (1995) proposed the Normalized Difference Snow Index (NDSI, [VIS – SWIR] / [VIS + SWIR]) technique for identification of snow. Racoviteanu *et al*. (2008a) successfully used the NDSI for glacier mapping of Cordillera Blanca. Sidjak and Wheate (1999) obtained best results using a combination of principal components two, three and four of the masked glacier area, the ratio TM-4/TM-5, and the NDSI. However, semi-automatic methods failed in the accurate mapping of debris cover due to a similar spectral signature of surrounding bedrock.

In the Indian Himalayas, few studies have been carried out with automatic glacier mapping techniques. Racoviteanu *et al*. (2008b) used the NDSI method for mapping glaciers of the Sikkim Himalayan region. Gupta *et al*. (2005) mapped dry/wet snowcover in the upper Bhagirathi basin (Gangotri Glacier) using the NDSI technique on digital IRS-LISS-III multispectral data. Kaushal *et al*. (2004) used the ratio of IRS LISS III band 4 (SWIR band) and band 3 (Red band) for snow mapping in Siachen Glacier area using IRS LISS data. Philip and Sah (2004) used merged IRS ID LISS III and PAN product for the study of glacier landform mapping of the Shaune Garang Glacier. The results of these studies indicate that these methods are useful for clean-ice glacier delineation/detection, but when used for debris-covered glaciers the results are not very encouraging. This is confirmed in Figure 4, where NDSI (1-4/1+4) and different band combinations for the ratio method (1/3 and 3/4 band) on ASTER images were used for glacier mapping of the Garhwal Himalayas. The observations are summarized as follows:

(1) NDSI and Band ratio method could not differentiate the extent of debris-covered glacier ice, as a result of the similar spectral signature from the surrounding debris;
(2) NDSI and Band ratio VIS/NIR misclassified proglacier lakes in threshold glacier areas, whereas Band ratio NIR/

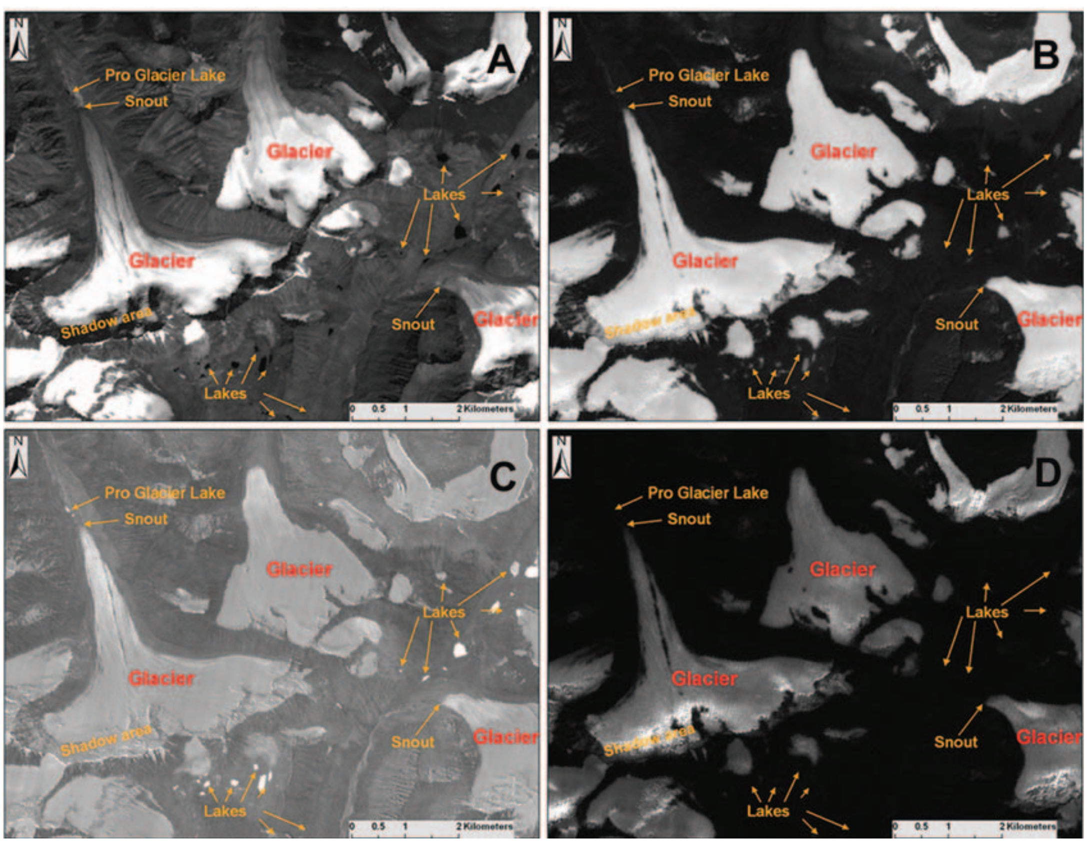

Figure 4 (A) Band 3 of ASTER image of the Garhwal Himalayas (2006). (B) NDSI image (1–4/1+4). (C) Band ratio (1/3). (D) Band ratio (3/4)

SWIR classified only clean glacier ice, therefore Band ratio NIR/SWIR is a more appropriate method for clean glacier ice than NDSI;
(3) in addition, Band ratio NIR/SWIR performs better than NDSI in the case of shadow areas.

3 Mapping of debris-covered glaciers

As illustrated above, clean-ice glaciers can be mapped automatically using multispectral images. However, many glaciers in the Himalayas are characteristically covered with thick debris mainly due to large volumes of debris-laden ice avalanche and rockfall on glacier surface from steep surrounding slopes (Shroder *et al*., 2000). Several studies have shown the applicability of morphometric parameters derived from DEM and thermal band in the mapping of debris-covered glaciers. Ranzi *et al*. (2004) used thermal signature from ASTER and Landsat imagery for debris-covered glacier mapping. This method is based on the fact that the surface temperatures of the debris layer superimposed on a glacier's ice is cooler than on the surroundings without ice. However, this is limited to debris layers thinner than 40–50 cm. Bishop *et al*. (2001) successfully showed that morphometric parameters such as slope, plan and profile curvature help to differentiate debris-covered glaciers from surrounding moraines. Paul *et al*. (2004) presented a semi-automatic method for delineation of debris-covered glaciers in the Swiss Alps, which combines multispectral image classification (glacier ice, vegetation) with DEM data (24-degree slope), neighbourhood analysis (connection to glacier ice), and change detection. Bolch and Kamp (2006) proposed a simple morphometric glacier mapping approach (MGM) based on plan curvature and profile curvature. Bolch *et al*. (2007) presented an automated but complex morphometric-based approach to outline the debris-covered glaciers of the Mt Everest Area (Nepalese Himalayas) based on the altitude, slope, plan and profile curvature derived from ASTER DEM as well as thermal bands of ASTER. Thus, all the proposed methods are region-specific, not universally established, and are optimized only for a small region. The suitability of ASTER DEMs has been established, but the results seem to be feasible for larger valley glaciers (>1 km^2) with well-defined lateral moraines.

In the Himachal Himalayas, Kulkarni *et al*. (2005; 2007) manually delineated debris-covered glaciers using IRS satellite data (Table 3). These studies assumed that grass cover seen in the months of August and September on terminal moraine can be used as a clue to delineate debris-covered glaciers. However, this technique failed in the case of the heavily debris-covered Chaurabari Glacier. During fieldwork in the months of August and September 2006 we observed that the terminal moraine near ablation zone was devoid of any vegetation.

We tested the applicability of the morphometric approaches in the Himalayan region and generated an ASTER DEM for the Garhwal Himalayas at 30 m spatial resolution using 11 GCPs derived from SOI topographical map and 129 TPs for image matching with 0.7 pixel RMS errors. Morphometric parameters such as slope, aspect, plan and profile curvature map were generated using SAGA. These parameters help to delineate the snout of Gangotri Glacier. This method is potentially suitable for mapping of debris covered-snout of Gangotri Glacier (Bhambri *et al*., unpublished data).

IV Measurement of glacier volume changes based on digital elevation models

1 Generation of digital elevation models

Digital elevation models (DEM) are valuable tools for mapping, modelling, analysing and visualizing of glacio-geomorphic phenomena in glacial environment (Etzelmüller and Sollid, 1997; Etzelmüller *et al*., 2001; Bolch *et al*., 2005). DEMs play an important role in the preparation of ortho-images in high mountain terrain (Finsterwalder, 1984), in estimating glacier hypsometry (Brocklehurst and Whipple, 2004), in the atmospheric correction of satellite imagery (Bishop and Colby, 2002) and in derivative parameter maps such as slope, plan and profile curvature, aspects of which can be further used for debris-covered glacier mapping (section III, 3). Furthermore, DEMs are most important for the estimation of volume change for inaccessible glacier regions (Rignot *et al.*, 2003; Surazakov and Aizen, 2006; Berthier *et al.*, 2007; Schiefer *et al.*, 2007; Bolch *et al.*, 2008).

DEMs can be prepared by different methods, such as space- and airborne optical stereo data, interferrometric SAR (InSAR) data, space and airborne radar and laser alimentary (eg, LiDAR), and topographic maps. The accuracy of the DEM derived from remote sensing depends on several factors, such as spatial resolution of satellite data, positional and vertical accuracy of ground control points (GCPs), and contrast and cloud cover in optical satellite images. GCPs can be computed for DEM generation mainly from three methods: highly precise DGPS measurements during fieldwork; existing rectified topographic maps; and from known satellite positions and rotation angles, where DGPS measurements and topographic maps are not available. This method depends on software capability (Kääb *et al.*, 2003). Berthier *et al.* (2007) used this method for collection of GCPs in the western Himalayas for the estimation of glacier elevation changes.

Terra ASTER is the most economical optical stereo satellite data on 15 m spatial resolution, which is the primary source of DEM generation under GLIMS Project (Kargel *et al.*, 2005; Raup *et al.*, 2007). SPOT-5, ALOS PRISM, CartoSat I and II, IKONOS, Quickbird and GeoEye-1 are the other satellites which offer stereo capability and can be used to monitor the glacier surface in three dimensions. Terra ASTER and ALOS PRISM offer along track stereo capability with quasi-simultaneous image acquisition, while the other sensors offer across-track acquisition where the timelag in the acquisition may cause problems (eg, due to clouds, different atmospheric conditions). SPOT 5 and ASTER have the highest coverage area (~60 × 60 km) compared with other satellite data.

Less contrast and cloud cover in satellite data can hamper the identification of suitable tie points and can lead to data gaps or elevation inaccuracies in output DEM which in turn can affect the results regarding volume changes. Therefore, it is essential to know elevation inaccuracies using RMS errors in glaciated regions based on existing highly precise DEMs and fieldwork. DGPS, GPS readings and more details about accuracy assessments in glaciated terrain are described in Table 4.

2 Deriving glacier volume changes and glacier mass balance

Literature survey reveals that estimations of glacier volume are mostly based on the area using: (1) volume/area scaling (Chen and Ohmura, 1990; Bahr, 1997); and (2) the AAR/ELA method (Kulkarni, 1992; Rabatel *et al.*, 2005). Kulkarni *et al.* (2004) estimated the mass balance of 19 glaciers in the Baspa basin, Himachal Pradesh, using the accumulation area ratio (AAR) method. This method utilizes a regression equation between AAR and specific mass balance, derived from unpublished field data collected by the Geological Survey of India during 1982–88 for Shaune Garang Glacier, and 1976–84 for Gor Garang Glacier. The AAR for 2000 and 2001, obtained by systematic weekly analysis of WiFS images from the IRS satellite from May to September, has also been estimated. Field measurement is frequently required for direct monitoring of traditional mass balance calculation. This method, like any other detailed field survey, is time-consuming and poses the potential risk of long stays in rugged and

Table 4 Selected studies on volume change/mass balance estimations

Authors	Location	DEM source	Vertical accuracy (m)	Brief observations and outcomes
Østrem and Haakansen (1999)	Norway	Topographic maps	±0.75	This study estimated that the lower part of the glacier has lost up to 24 m of ice near its front and total mass loss was calculated as 5.8 m of water equivalent
Vignon *et al*. (2003)	Cordillera Blanca, northern Peru	Topographic maps, ASTER	Topographic maps – ±10 ASTER – ±22	This study estimated the volume change of three small glaciers in Cordillera Blanca and found a small valley glacier had lost 47.10^{6} m of water equivalent from 1962 to 2001
Rivera *et al*. (2005)	Southern Patagonia	Aerial photographs, ASTER, GPS data	GPS data – ±0.30 Aerial photo – ±8.5 ASTER – ±22	This study found a maximum ice thinning of 54±0.55 m a^{-1} observed at the glacier front from 1975 to 1997 that was slightly supported by GPS data which indicated a thinning rate of 1.9±0.14 ma^{-1} during 1998–2001. This study estimated a mean net glacier mass balance of –0.29±0.097 km^{3} w.e. a^{-1} from 1975 to 2001
Berthier *et al*. (2006)	French Alps	SRTM, SPORT5, IGN DEM	SRTM – ±15.7 SPORT5 – ±1.1, IGN DEM – ±21.2	This study evaluated absolute accuracy of SRTM data for the monitoring of glacier volume variations
Keutterling and Thomas (2006)	Gepatschferner glacier, Austria	Aerial photos, topographic map	Aerial photos DEM – ±2.25 Topographic map – ±6	This study estimated a net loss of 26×10^{6} m^{3} glacier volume (approximately 0.9%) from 1971 to 1990 in northern Tyrol, Austria
Surazakov and Aizen (2006)	Akshiirak glaciers (Tien Shan, central Asia)	Topographic maps, SRTM	Topographic maps – ±3.3 SRTM – ±17	This study estimated that the volume loss of Akshirak glacier increased by 2.7 times during 1977–2000, compared with historical data from 1943 to 1997; this study found that the errors in surface change increased with the increase in slope
Berthier *et al*. (2007)	Himachal Pradesh (western Himalayas, India)	SRTM, SPORT5	SRTM – ±18 SPORT5 – ±25	This study found the rate of ice loss was two times higher during 1999–2004 than the previous long-term (1977–99) mass balance records for the Himalayas

(*Continued*)

Table 4 *Continued*

Authors	Location	DEM source	Vertical accuracy (m)	Brief observations and outcomes
Schiefer *et al*. (2007)	British Columbian glaciers, Canada	Aerial photographs, SRTM, topographic maps	Aerial photographs – ±5 SRTM – ? Topographic maps – ±25	This study found significant elevation bias in the SRTM elevation of the glaciated region which can lead to erroneous estimation of volume changes. After bias correction, the thinning rate was estimated at –7.8±0.19 ma^{-1} in this study
Pope *et al*. (2007)	Svalbard	Aerial photographs	-	This study presented a method of assessing the quality of derived surface through a detailed sensitivity analysis of the DEM collection parameters through a multiple input failure warming model (MIFWM). This study mainly concentrates on DEM quality analysis
Rivera *et al*. (2007)	Northern Patagonia ice field, Chile	Topographic maps, ASTER	Topographic maps – ±19 ASTER – ±26	This study mapped glacier boundaries from topographic maps and satellite images and also estimated high thinning rates (up to –4.0±0.97 ma^{-1}) at CHN from 1975 to 2001
Racoviteanu *et al*. (2007)	Nevado Coropuna, Peruvian Andes	Topographic maps, ASTER, SRTM	SRTM – ±23 ASTER – ±61 Topographic maps – ±14.7	This study evaluated the SRTM, ASTER and topographic DEM using GPS data for glaciological application, and found an average thinning of ±5 m at the glacier surface with a significant lowering of the glacier surface at the glacier toes
Bolch *et al*. (2008)	Khumbu Himalayas	ASTER , Corona KH-4	ASTER – ±30 Corona KH-4 – ±56	This study estimated 0.19 km^3 volume loss for debris-covered glacier tongues from 1962 to 2002 and found highest downwasting rate >0.5 m/a for the Khumbu Glacier from the active to stagnant glacier part of the debris-covered glacier tongue
Bahuguna *et al*. (2004; 2007)	Himachal and Garhwal Himalayas	IRS IC and ID PAN	±15 m	These studies estimated vertical accuracy of DEM based on SOI topographic maps
Paul and Haeberli (2008)	Swiss Alps	National DEM, SRTM	Swisstopo DEM – ±8	This study estimated elevation changes for the *c*. 1050 glaciers in the Swiss Alps by differencing the SRTM3 DEM from a national DEM (1985). This study revealed extreme thickness losses (>80 m) for flat/low-lying glacier tongues and a strong overall surface lowering

extreme weather conditions, which in turn has financial implications. Hence, surface changes derived from DEMs, known as indirect geodetic methods, could be a useful tool to calculate the glacier volume changes and mass balance estimation (Etzelmüller and Sollid, 1997). This method is based on the assumption that a change in elevation (dh/dr) over time from DEM constructed over the glacier region from various sources (section IV, 1) can be translated into a change in mass. This method holds true if: (1) there is no change in elevation on the bedrock due to neo-tectonic activities; and (2) the density of ice mass has not changed (Bamber and Rivera, 2007). However, the accuracy of mass balance and volume change estimation derived from geodetic method is governed by several factors, such as:

(1) error generation during DEM generation using optical stereo satellite data due to saturation of pixels, shadow areas, low contrast in imageries;
(2) error in DEM generation using radar data due to radar shadow, foreshortening, layover, and penetrating into snow;
(3) error generation from scanning of old topographic maps and digitization of contours and interpolation for conversion of digitized contours into surface (pixels);
(4) error generation during ellipsoid and datum conversion for subtraction of different DEM derived from various sources;
(5) error generation during changes in spatial resolution for the subtraction of various DEMs;
(6) errors occurring from assumption of constant value for loss and gain of density of ice/firm;
(7) error generation during rectification of old topographic maps and satellite images.

Thus, the accuracy of volume change/mass balance estimation depends on the accuracy of the DEMs generated from various sources. Aerial photographs and most topographic maps of the Indian Himalayas are not in the public domain. Therefore, the subsequent reference DEMs cannot be generated. To date, only one study has been published (Berthier *et al*., 2007) for the mass balance estimation of the Himachal Himalayas using SRTM and SPOT-5 satellite data (Table 4).

V Challenges in comparing data sets from different sources

Different data sets obtained at different times have inherent differences in resolution, reference system, interpretation bias and the classification techniques adopted. However, recent developments in geo-informatic software facilitate rectification, reprojection, and error detection and allow analysis of these potential error sources. Nevertheless, results of different studies in similar regions do not always match, and thus induce uncertainty in the scientific understanding of the problem. Creation of metadata is being promoted to facilitate the reinterpretation of the data sets by other users.

Topography maps published by the SOI generated from aerial photographs have serious accuracy issues, specifically in the case of ice-covered (Vohra, 1980) and debris-covered glaciers. This is attributed mainly to cartography skills and the time of aerial photography acquisition during early winter months after snowfall (Agarwal, 2001). A review of the history sheets for 12 topographic maps of Himachal Pradesh also shows that 10 topographic maps were prepared from aerial photographs taken in November/December (Table 5). The timing of aerial photography makes it very difficult for even a skilled image interpreter to distinguish the snout from the surrounding moraines which can result in errors in the delineation of glacier outlines.

Vohra (1980) found differences in the length of the debris-covered Gara Glacier based on the SOI topographic map and field investigation. The length of the clean-ice segment of Gara Glacier has been reported to be 5.5 km. Well-developed terminal moraines beyond the debris-covered glacier segment were falsely interpreted and indicate a length

Table 5 Details of aerial photographs used in the preparation of topographic maps of Himachal Pradesh

Topographic map number	Date of aerial photography	Scale		Publication year
		Topographic map	Aerial photo	
53E/9/NE	Nov/Dec 1975	1:25,000	1:50,000	2002
53E/9/SE	28 Nov 1975			
53E/9/NW	Nov/Dec 1975			
53E/13/NW	Nov/Dec 1975			
53E/13/SW	28 Nov 1975			
53E/10/NW	Nov/Dec 1975			
53E/10/SW	11 Dec 1975			
53E/10/SE	11 Dec 1975			
53E/10/NE	11 Dec 1975			
53E/05	June 1960	1:50,000	1:70,000	1968
53E/09	08 June 1962		1:60,000	
53E/13	March 1962			

of 7 km, amounting to an increase of 27.3% in length. Basically, it can be difficult for cartographers to distinguish the actual debris-covered glacier terminus, which results in misclassification of well-developed terminal moraines as glacier boundaries. Agarwal (2001) reported significant differences in aerial extent of Gor Garang and Shaune Garang Glaciers in the GSI unpublished reports. Glacier outlines derived from topographic maps suggest an area almost twice as great as that of field survey glacier map outlines (Table 6). Mukherjee and Sangewar (2001) used the sketch of the Gangotri Glacier snout prepared by Griesbach in 1889, the SOI topographical map (1962), SPOT imagery and vertical aerial photographs for a Gangotri Glacier recession study. They calculated an advance of the snout of about 500 m until 1935 with respect to the position in 1889, whereas Sharma and Owen (1996) and Naithani *et al*. (2001) indicate that the Gangotri Glacier has been retreating since 1780. It is noteworthy that the sketch prepared by Griesbach could not be overlain accurately, as it is a rough sketch map of the 1889 situation while the other was produced by modern photogrammetric methods with limited fieldwork.

The debris-covered Chaurabari Glacier is the source of the Mandakani River in the Garhwal Himalayas. The glacier outline of the Chaurabari Glacier derived from the 1962 SOI topographic map does not clearly show the boundary of the glacier, nor of its companion glacier (Srivastava *et al*., 1995). Our own investigations based on Landsat MSS, TM, ETM+ and Terra ASTER satellite images from the years 1972, 1990, 1999, 2003 and 2006 indicate that the Chaurabari Glacier has one companion glacier which flows from the northwest (Figure 5). We overlaid the 1962 glacier outline on Landsat MSS (1972) and ASTER (2006) satellite images, which indicated a shift in the ice divide and cliff face. A rocky cliff is a rigid geomorphic feature which can be assumed not to shift within the very short timespan, geologically speaking. This overlay operation implies a mapping error in the delineation of glacio-geomorphic features of the Chaurabari Glacier in the SOI maps.

On the basis of modified map of Auden, Srivastava (2004) estimated a 0.58 km^2 area

Table 6 Area difference in Gor Garang and Shaune Garang Glaciers in topographic map and field survey (from Agarwal, 2001)

Glacier name	Area (km^2)	
	Topographical map SOI	Field survey
Gor Garang	4.33	2.02
Shaune Garang	8.12	4.94

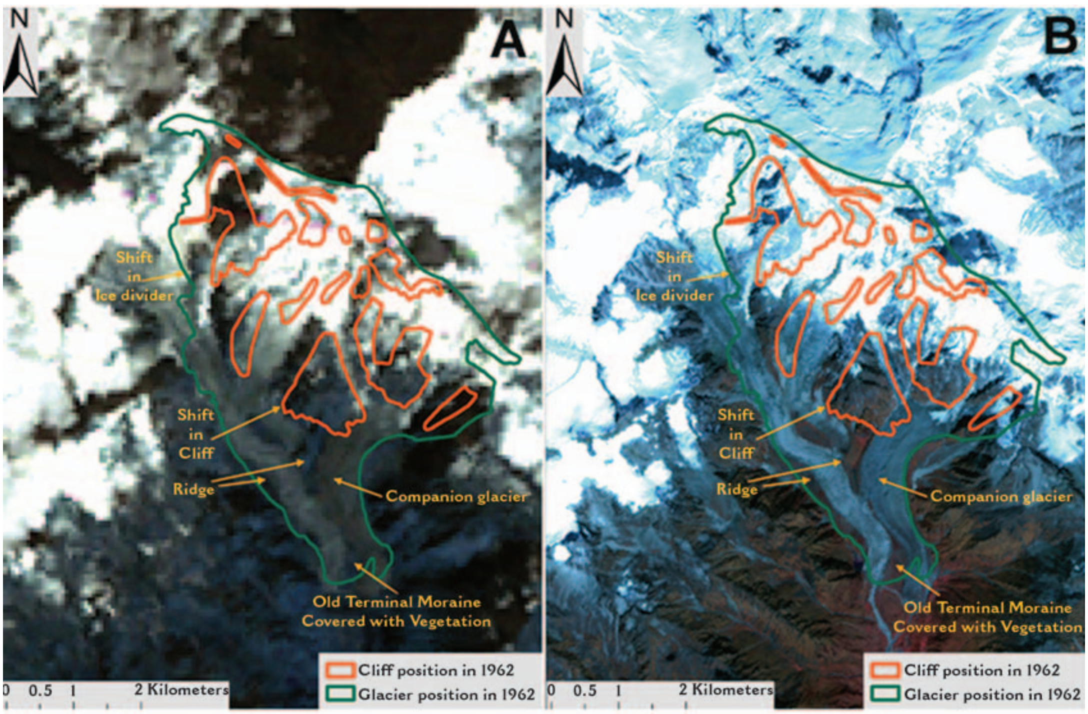

Figure 5 Overlay of glacier and cliff outlines from topographic map on different years' satellite images. (A) 1972 MSS FCC image. (B) 2006 ASTER FCC image

loss of ice on the Gangotri Glacier from 1935 to 1996 whereas Ahmad and Hasnain (2004) estimated a 20 times greater loss (10 km^2) at this glacier from 1985 to 2001 based on topographic map and satellite image (Table 7). The area of Gangotri Glacier calculated by Sharma and Owen (1996) and Ahmad and Hasnain (2004) does not accord well with the GSI studies by Srivastava (2004) and Dutta *et al*. (2004) (Table 7).

Kulkarni *et al*. (2005) calculated a 48.44 km^2 area of the Parbati Glacier based on the SOI topographic map nos. 53 E/9 and 13 (1962), and 40.14 km^2 from a 1990 satellite image, which reveal that the area loss amounted to 8.3 km^2 in 28 years. Fortunately, the SOI produced a revised topographic map nos. 53E/9 and 13 from surveys done in 1987 and published in 2002. These maps are available at the scale of both 1:50,000 and 1:25,000. For this study, these topographic maps were registered with RMS errors of 1.8 m (1:25,000) and 3.7 m (1:50,000). The area of the Parbati Glacier was calculated

Table 7 Area of Gangotri Glacier estimated by various Indian scientists and organizations

Authors	Area (km^2)	Mapping reference
Sharma and Owen (1996)	87.08	Huber topographic map (1:150,000)
Ahmad and Hasnain (2004)	87	Survey of India topographic map 1985
Ahmad and Hasnain (2004)	77	IRS Pan Image, 2001
Srivastava (2004), GSI	143.58	Topographic map 1966 (1st edition), SOI with fieldwork modification

Table 8 Area and length parameters of Parbati Glacier

Authors	Area (km^2)	Mapping reference	Length (m)	Scale
Kulkarni *et al.* (2005)	48.44	SOI topographic map 1962 surveyed	16,689	1:50,000
Kulkarni *et al.* (2005)	40.14	1990 satellite image	10,698	–
Present study	44.78	SOI topographic map 1987 surveyed	12,672	1:50,000
Present study	44.68	SOI topographic map 1987 surveyed	12,499	1:25,000

at 44.78 km^2 and 44.68 km^2 for the scales of 1:50,000 and 1:25,000, respectively. This indicates an area of 0.1 km^2 less in the map having a scale of 1:25,000 in comparison to the 1:50,000 scale map. In addition, the ice-covered area diminished by 3.66 km^2 in 25 years on the basis of 1962 and 1987 topographic maps (Table 8). A comparison of the calculated area of the Parbati Glacier based on a 1990 satellite image (Kulkarni *et al.*, 2005) with the area calculated based on the 1987 topographic map reveals that an area of 4.64 km^2 was cleared of ice in three years – a rather unrealistic value.

In order to assess the positional accuracy of the Parbati Glacier region maps (53E/13 and 53E/13/SW) at the scales of 1:50,000 and 1:25,000 (1987 surveys), we used 50 common location points such as river junctions, road junctions and spot heights in both maps. We found a horizontal shift of 64 m on the map at a scale of 1:50,000, as compared to the 1:25,000 scale map. An overlay operation of the glacier outline of both maps confirmed the planimetric shift, with a 179 m difference in length from both the maps estimated from the central line of the glacier (Table 8).

VI Glacier variations since the Little Ice Age in the Indian Himalayas

The Geological Survey of India and other scientific Indian organizations have at their disposal almost 100 years of well-documented recession records of the lengths of selected Garhwal and Lahul Spiti glaciers, such as Gangotri (1842–2006), Meola (1912–2000) and Milam (1906–97) Glaciers. Gangotri, Dokriani and Chotta Shigri Glaciers have been surveyed extensively by several researchers working on mass balance, hydrological, geomorphological, isotopic and glacier recession. The Integrated Centre for Mountain Development (ICIMOD) – Asia Pacific Network organized a glacier inventory study on Himachal Pradesh, Uttarakhand and Sikkim in 2003–2004 (Campbell, 2005). However, this study has not been carried out in Kashmir and Arunachal Pradesh. Recently, the Space Application Centre (SAC) has started glacier change studies in 15 subbasins of the Indian Himalayas, particularly: the Alaknanda, Bhagirathi, Dhauliganga, Goriganga and Mandakini (subbasins of the Ganga basin); the Chandra, Bhaga, Miyar, Warwan and Bhut (subbasins of the Chenab basin); the Ravi and Spiti basins in the Himachal Himalayas; the Suru and Zanskar basin in the Kashmir Himalayas; and the Tista basin in the Sikkim Himalayas (Bahuguna, 2008).

A study by Mayewski and Jeschke (1979) indicates that Himalayan glaciers have been receding since 1850. The length recession records of Himalayan glaciers (Figure 6; Table 9) indicate that glacier retreat is irregular in extent and rate. However, these records have to be used with caution due to the different response time of the glaciers. Overall, the recession of the glacier tongues has accelerated since the 1960s. For instance, in Bhagirathi basin, Dokriani Glacier retreated at the rate of 16.6 m/a during 1962 to 1995, and from 1995 to 2000 it retreated 18.5 m/a (Dobhal *et al*., 2007). Chotta Shigri Glacier in the Chandra basin retreated 27.5 m/a from 1962 to 1989, and 53 m/a during 1988 to 2003 (Kulkarni, 2007).

In the Alaknanda basin, the ice-covered area of Satopanth Glacier diminished by 313.9 m^2 (0.0015%) near the snout from 1962 to 2006, whereas Bhagirathi Kharak Glacier lost an area of 129.4 m^2 (0.0004%) during a similar time period (Nainwal *et al*., 2008). These two glaciers are situated in the same basin and likely experienced similar climatic conditions. However, both glaciers are reported to be retreating at different recession rates. Bhagirathi Kharak and Satopanth Glaciers retreated 7.4 m/a and 22.8 m/a during 1962 to 2006, respectively. This might be due to uneven distribution of tributary glaciers, active cirques, drainage density and distributions of supraglacial debris cover (Nainwal *et al*., 2008).

Kulkarni *et al*. (2007) reported glacial retreat for 466 glaciers in the Chenab, Parbati and Baspa basins (Himachal Himalayas) from 1962 to 2001–2004. This investigation estimated that 21% (~0.52%/a) of the glacier area was deglaciated from 1962 to 2001–2004. The amount of retreat varies between 22% (Parbati basin) and 19% (Baspa basin) during the above period. Kulkarni *et al*. (2007) concluded that the number of glaciers increased between 1962 and 2001 due to disintegration of larger glacier masses. This study suggests that glaciers <1 km^2 lost 38% (~.095%/a) of their 1962 area, which reveals that small Himalayan glaciers are retreating at a high rate due to slight or negligible accumulation. Similarly, several studies outside the Himalayas such as in the Swiss Alps suggest that glaciers <1 km^2 lost 57% of their area (~1.48%/a) during 1973 to 2000 (Zemp *et al*., 2007). The inner Tien Shan (Terskey Alatoo) glaciers <1 km^2 lost 40% of their area (~1.29%/a) during 1971 to 2002 (Narama *et al*., 2006). Similar tendencies can be found in many other part of the world, eg, the northern Tien Shan (Bolch, 2007) and western Canada (Bolch *et al*. 2009). This indicates that small glaciers retreat more rapidly than the larger ones.

Kulkarni (2007) estimated that the average altitude of the snow-line at the end of the ablation season is 5400 m and 5297 m for south- and north-facing glaciers, respectively, in Himachal Pradesh. Generally, the combined influence of altitudinal distribution and little or no accumulation zone is likely to be the major cause of the rapid recession of the small glaciers. For example, Nagpo Tokpo Glacier in Spiti subbasin (Satluj basin) is located in the 5240 m to 5720 m altitude range. It receded 65 m/a during 1963 to 1998. Available fluctuation records of Indian glaciers suggest that, for north- and northeast-facing glaciers in the Bhagirathi basin, such as Gangotri and Meru Glaciers, the recession rate fell after 1990, whereas the Parbati and the Bada Shigri Glaciers are retreating dramatically. Commonly, south-, southeast- and southwest-facing glaciers, such as Jaunder, Jhajju and Tilku Glaciers in the Tons Valley, are receding rapidly at a rate of more than 30 m/a. These valley

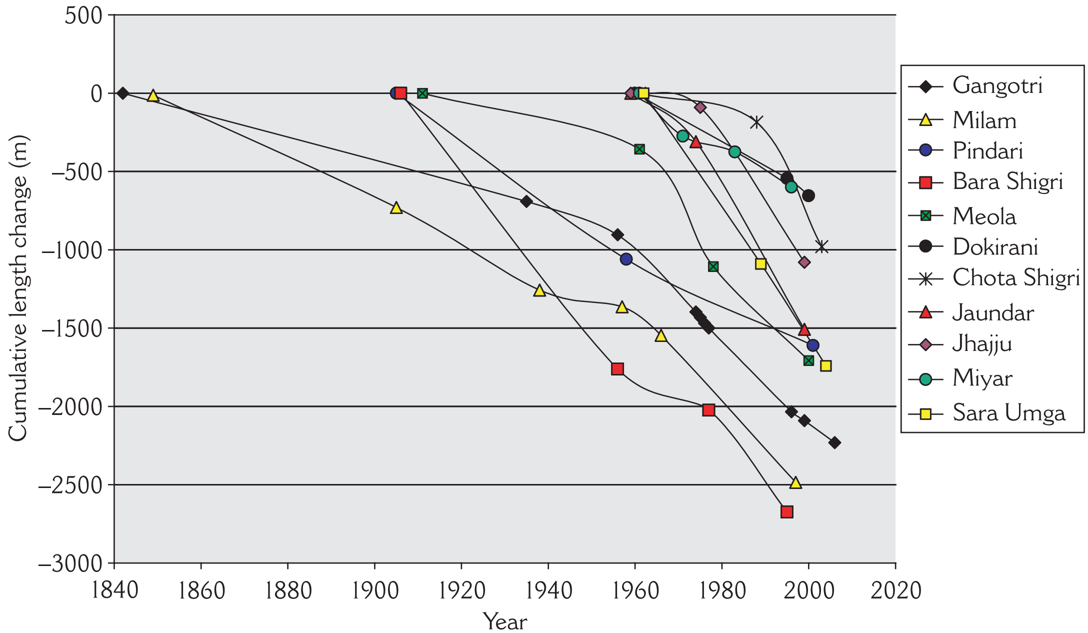

Figure 6 Cumulative length changes of selected Indian Himalayan glaciers; the markers indicate the years of measurements (see Table 9)

glaciers accumulate under the influence of the southwestern monsoon. Published records (Table 9) suggest that glaciers longer than 15 km retreat at a rate of more than 20 m/a, except for Miyar and Gangotri Glaciers, and, furthermore, the recession of these glaciers has accelerated compared with the previous observation. These observations suggest glacial retreat in Dauliganga, Gori Ganga basin, such as Jhulang (11 m/a) and Burpu Glaciers (5 m/a), increasing in the Tons Valley of Yamuna basin, reaching a maximum in the Parbati, Chenab and Baspa basins (Figure 1). Kulkarni *et al*. (2005) estimated an average recession rate of 173 m/a for the Parbati Glacier from 1962 to 2001 and predicted that the main glacier body would continue to retreat at almost the same rate until 2022. Almost 24% of the area of the Parbati Glacier was deglaciated from 1962 to 2001, whereas Dokriani Glacier lost about 11% of its previous area in during 1962–95.

The Snow and Avalanche Study Establishment (SASE) have established a network of 50 manned metrological observatories and 40 automatic weather stations in the northwestern Himalayas (Negi *et al*., 2007). This climatic data could be used for interpretation at micro-level for the fluctuation of particular Indian Himalayan glaciers.

VII Discussion

1 Historical and recent glacier mapping

Historical glacier mapping in the Himalayas was dependent on risky and time-consuming field investigations involving the use of heavy survey equipment. Today, remote sensing images and techniques facilitate glacier mapping and the investigation of recent glacier fluctuations in less time for remote mountainous areas. In India, however, most studies on glacier mapping delineate glacier outlines using time-consuming on-screen digitization. Automated mapping of clean glacier ice has been successfully attempted on the Sikkim Himalayas and can be applied in other parts of the Himalayas as well

Table 9 Recession records of selected Himalayan glaciers

Glacier	Basin	Length (km)	Area (km^2)	Orientation	Snout height (m a.s.l.)	Snout height measurement year	Record of fluctuation in years	Recession (m/y)	References
Gangotri	Bhagirathi	30	143	NW	3902	1996	1842–1935	7.35	Auden (1937), Srivastava (2004), Naithani *et al*. (2001), Thayyen (2008)
							1935–1956	10.16	
							July 1956–March 1962	18.75	
							March 1962–September 1971	32.21	
							1971–1975	28.87	
							1975–1977	36.50	
							1977–1990	28.80	
							1935–1996	18.8	
							1996–1999	19	
Milam	Goriganga	18	53.95	SE			1849–1906	12.8	GSI (1996–97)
							1906–1938	16	
							1938–1957	5.6	
							1957–1966	20.2	
							1966–1997	30.3	
Burphu	Goriganga		11.85	SW			1966–1997	4.84	GSI (1996–97)
Dunagiri	Dauliganga		2.56	N	4240	1984	1992–1997	45–60 total advancement	GSI (1996–97)
Chaurabari	Mandakani	7		S	3840		1992–1997	25–55 m total in 5 years	GSI (1996–97)
Hamta	Chandra	6	4.5	S	4020	1998	1963–1998	17.14	GSI (1997–98)
Nagpo Tokpo	Spiti (Satluj)	2.7	2.51		5240	1998	1963–1998	65.71	GSI (1997–98)
Bandarpunch	Tons (Yamuna)	11.80	22.79		3940	1999	1960–1975	41.33	GSI (1998–99)
							1975–1999	15.63	
Jaunder Bamak	Tons (Yamuna)	19.10	57.08	S	3880	1999	1960–1975	20.67	GSI (1998–99)
							1975–1999	47.92	
Jhajju Bamak	Tons (Yamuna)	4.5	5.70	S	3880	1999	1960–1975	5.67	GSI (1998–99)
							1975–1999	41.25	
Tilku	Tons (Yamuna	4.35	2.44	S	4200	1999	1960–1975	5.33	GSI (1998–99)
							1975–1999	32.29	

(*Continued*)

Table 9 *Continued*

Glacier	Basin	Length (km)	Area (km^2)	Orientation	Snout height (m a.s.l.)	Snout height measurement year	Record of fluctuation in years	Recession (m/y)	References
Chipa	Dauliganga	9.95	5	E	3527	2000	1961–1978	32.35	GSI (1999–2000)
							1978–2000	22.72	
Meola	Dauliganga	10.3	14.02	E	3460	2000	1961–1978	44.12	GSI (1999–2000)
							1978–2000	27.27	
Jhulang	Dauliganga	7	3.27	NE	3920	2000	1962–2000	10.53	GSI (1999–2000)
Beas Kund	Beas	2.1		NE			1963–2003	18.75	GSI (2002–03)
Jobri	–	3		NW			1963–2003	2.5	GSI (2002–03)
Mantalai	Parbati	6.5	11.70	NE			1989–2004	23.3	GSI (2003–04)
Sara Umga	–	15.25	55.89	SW	3882	2004	1963–1989	40.4	GSI (2003–04)
							1989–2004	43.3	
Bhagirathi Kharak	Alaknanda	17		E	3780	2006	1962–2006	7.3	Nainwal *et al.* (2008)
Satopanth	Alaknanda	14		E	3870	2006	1962–2006	22.8	Nainwal *et al.* (2008)
Pindari	Alaknanda			SW			1906–1958	20.00	GSI (2000–01)
							1958–2001	12.80	
Triloknath	Chenab	6.5	6.7	NW	3720		1969–1995	15.38	GSI (1994–95)
Chotta Shigri	Chandra		15.01	N			1962–1986	6.87	GSI (1994–95), Kulkarni (2007)
							1988–2003	53	
Bara Shigri	Chandra	29	137	NW			1906–1956	35	GSI (1994–95)
							1956–1977	11.35	
							1977–1995	36.11	
Nikarchu	Kuthiyankti	3.9	7.38	NE			1962–2002	9.37	GSI (2001–02)
Adikailesh	Kuthiyankti	2.3		NE			1962–2002	13	GSI (2001–02)
Ramganga	Kuthiyankti	3		S			1962–2002	50	GSI (2001–02)
Meru	Bhagirathi	7.6	4.7	NE	4330	2000	1977–1987	27.50	Chitranshi *et al.* (2004)
							1987–2000	9.23	
Miyar	Chandra – Bhaga (Chenab)	27.6	87.78	SE	3940	1996	1961–1971	25	Oberoi *et al.* (2001)
							1971–1983	8.33	
							1983–1996	17.30	

(Krishna, 2005; Racoviteanu *et al*., 2008b). However, mapping of debris–covered glaciers is still a challenging task, and, besides manual delineation, there is not yet a method devised which combines accuracy and a reduced amount of effort, although many debris-covered glaciers exist in the Himalayas. Prior studies on debris-covered glacier mapping, such as Paul *et al*. (2004), Bolch and Kamp (2006) or Bolch *et al*. (2007), have confirmed the relevance of DEM and thermal band information which can be applied in the Indian Himalayas. These will prove useful in the development of new methodologies for debris–covered glacier mapping in the Indian Himalayas. However, DEMs based on topographic contour are generally not available for the Indian Himalayas. Hence, the ASTER DEM provides a promising opportunity for mapping debris–covered glaciers. Its applicability has been established during the mapping of debris–covered glaciers in the Khumbu Himalayas, Tien Shan and the Alps (Bolch and Kamp, 2006; Bolch *et al*., 2007).

Several topographic glacier mapping studies, such as Workman (1903), Longstaff (1908; 1911), Visser (1926), Mason (1928), Shipton *et al*. (1938) and Mott (1950), have improved the previous maps and mapping methodology. In the current Indian scenario, however, glacier outlines based on remote sensing and GIS have not been available for the assessment of the adopted methodology due to the absence of a central database of digital glacier outlines on a country scale. In addition, a glacier inventory of the Indian Himalayas has not been executed in digital GIS format (Kaul, 1999). At present, efforts are being focused on including glacier outlines from the Himalayas in the GLIMS database (Racoviteanu *et al*., 2008b).

Historic glacier maps are very important for glacier research for two reasons: (1) to provide information on glacier extents into the past; and (2) to generate the contours on glacier area to assist in estimation of mass balance and volume change studies. The Survey of India publishes several maps covering glacier terrain features. Unfortunately, these maps contain inaccuracies and they are often based on aerial imagery with seasonal snowcover. It has been shown that the glacier extent on these maps can be erroneous, and the origin of the map must, therefore, be carefully checked and verified prior to use for further glacier studies.

The Geological Survey of India has mapped several glacier snouts and the surrounding glacio-geomorphic features for monitoring glacier variability since the twentieth century using plane-table mapping. Several studies by the GSI overlaid glacier outlines derived from plane-table maps onto satellite images and aerial photographs in order to find the recession rate of glaciers. However, in a practical sense, it is very difficult to identify common points on plane-table maps and satellite images for co-registration and to further overlay operations on map, satellite images and aerial photographs.

Recently, internet-based online cryospheric information system (CCIS) for several countries such as China facilitates further gathering of knowledge about the present state of glacier extent and glacier changes in their country (Li *et al*., 2003). The Institute of Cartography at the ETH Zurich demonstrated an internet-based Mountain Information System which is accessible for use by metadata, a visual tool relating to potential multihazards and multirisk in an alpine valley of Switzerland (Hurni, 2006). These maps support the planning efforts with regard to current water resources, and also help in designing policies for other disciplines, as regards the impact of climate change in ecosystems in mountain regions.

The errors incurred during the acquisition and analysis of glacier data in the Indian Himalayas are generally neglected, but they may have significant impacts on outcomes and conclusions. Several differences and inaccuracies in glacier mapping cannot be explained by climate and the topography alone. Each approach has a number of shortcomings, eg, errors in field surveying, plotting of glacier outlines on plane-table maps, coregistration of plane-table maps with topographic maps, satellite images and aerial photographs for overlay on glacier outlines, and inaccurate mapping of debris-covered glaciers. Application of techniques such as root mean square (RMS) error may be used to control the quality of the analysis and outcomes and to understand the impacts of errors on the outcomes and error propagation (Hall *et al*., 2003; Falorni *et al*., 2005). For instance, source information for each digitized glacier feature has been stored in the database of the British Ice Sheet (Clark *et al*., 2004). In addition, errors associated with DEMs have also been reported, as these may influence mass balance estimation (Berthier *et al*., 2006).

2 Glacier variations in the Himalayas

This review of multiple glacier records concerning length and area changes shows that glacier topography has been changing dramatically within the Indian Himalayas in the last few decades. Published records on Indian Himalayan glaciers indicate that the glaciers in the Chenab, Parbati and Baspa basins and the Garhwal Himalayas are generally in a retreating phase. However, regional trends of glacier fluctuations in Kashmir and Arunachal Pradesh are not widely known as the current fluctuation records are not available. In general, however, glaciers in the Himachal Himalayas are receding with an area loss of about 21% (~0.52%/a) at a much faster rate compared with regions in Nepal. As an example, investigations in the Tamor River basin/eastern Nepal conducted in 1970–2000 revealed that 5.88% (~0.2%/a) of the glacier area was deglaciated (Bajracharya and Mool, 2006). This is a higher rate than for the Khumbu Himalayas where Bolch *et al*. (2008) estimated, based on space imagery, a loss of ice-covered area of 5.2% (~0.12%/a) from 1962 to 2005. Salerno *et al*. (2008) estimated, based on topographic maps, that 4.8% (~0.12%/a) of the glacier area was deglaciated from the 1950s to the 1990s in Sagarmatha National Park, Nepal. The problems encountered in comparing maps, however, were also highlighted. In addition, it has to be noted that the large glaciers in the Khumbu area are covered with debris and the mass loss is recognizable mainly through downwasting (Bolch *et al*., 2008). Recession of glaciers around the Xingxinghai Lake region and the Nam Co Lake region in Tibet are estimated at about 0.5%/a (1970–2000; Yao *et al*., 2007), recession rates similar to those of the Himachal Himalayas. However, the retreat rate has increased since 1990 in Tibet. A similar conclusion was reached by Fujita *et al*. (2001) during the study of Glacier AX010 in the Shorong region of Nepal. On average, 26% of this glacier was deglaciated (~1.25%/a) from 1978 to 1999. However, this glacier is relatively small.

Glacier variability depends on several environmental conditions such as minimum and maximum temperature, solar radiation, and the amount of precipitation and debris-cover load, as well as altitude and orientation of the glacier, which influence the mass balance of the glacier. Climate change in mountain regions has been considered as an important factor in the interpretation of glacier variability (Beniston *et al*., 1997; Haeberli and Beniston, 1998). Instrumental records of climatic data of Shimla (over 100 years) indicate a post-monsoon increasing temperature trend (Borgaonkar *et al*., 1996), which accelerates the melting of monsoonal seasonal snowcover, and this is the constraint in the conversion of snow into glacier ice. Recently, instrumental weather records from the northwestern Himalayan region for the past century show an increase in temperature of around 1.6°C/100 years, with winters warming at a faster rate (Bhutiyani *et al*., 2007). Also this study found that significant warming started from the late 1960s and the highest rate of increase was in the last two decades, but no significant trend for precipitation has been found (Yadav, 2007). Outside the western Himalayas, Shrestha *et al*. (1999) found that maximum temperature trends have increased, ranging from 0.06°C to 1.2°C per year, in most of the middle mountains of the Nepal Himalayas. This indicates that temperature increase might be the major cause of the glacier recession. Debris-cover on glacier ice influences the ablation rate of glaciers, and ablation rate decreases with increases in the thickness of debris (Nakawo and Rana, 1999). The altitude of the accumulation zone is another key factor which influences the ablation of glaciers (Kulkarni, 2007). Generally speaking, Himachal Himalayan glaciers are located at low altitudes (Kulkarni *et al*., 2007), whereas Garhwal Himalayan glaciers are located at high ones.

Overall, the north–south and east–west irregularity of Himalayan glacier recession is affected by: snow shadow zone effects; east-to-west and south-to-north decreases in monsoonal intensity; distributions of supraglacial debris cover; altitude of accumulation zone (Kulkarni, 2007); and contributions from tributary glaciers in accumulation zones (Nainwal *et al*., 2008). It is predicted on the basis of regional climate models (RCM) that the temperature in the Indian subcontinent will rise by 3.5–5.5°C by 2100 (Kumar *et al*., 2006). This will have an enormous impact on the glaciers. Glacier water resources are likely to diminish and glacier-related hazards are likely to increase (Kääb *et al*., 2006).

VIII Conclusions and recommendations

This review provides a comprehensive overview of the constraints and challenges relating to mapping of clean-ice and debris-covered glaciers, the comparison of different data sets and of the estimation of glacier volume changes based on multitemporal digital elevation models in the Indian Himalayas. There is a need for improvement, and possible solutions are suggested. SOI maps are imprecise for glacier terrain in some instances. Declassified imagery from intelligent spy satellites, such as Corona imagery from the 1960s and 1970s, can be used for confirmation and improvement of the glacier outlines derived from the Survey of India maps. Glacier change studies have not been carried out over the entire Kashmir Himalayas and Arunachal Pradesh. Therefore, current efforts should focus on the generation of glacier fluctuation records from satellite images and general trends should be identified based on the study of individual basins. It is suggested that a central database for glacier outlines on a country scale in India should be maintained. In addition, glacier mapping studies based on remote sensing and GIS should include information on data quality, data error, and error propagation. Metadata should be generated during glacier inventory which can assist other investigators when comparing previous studies.

Several reports and research documents were found not to be publicly available; the sharing of research documents and data would clearly lead to the enhancement of scientific knowledge and assist in the development of new models and methods for glacier mapping, mass balance and sea-level estimations. Moreover, this would also allow others to scrutinize previous studies and improve techniques and methodology. Therefore, it is recommended that research work in the form of technical reports, research papers, maps or unpublished reports, glacier inventory data and results, mass balance data, and glacier maps be declassified and published.

It was shown that automated and semi-automated mapping of debris-covered glaciers is almost unknown for Himalayan glaciers, and there have been almost no studies published so far. Therefore, it is recommended that current efforts focus on the development of suitable automated mapping methods for debris-covered glaciers. In India, in the absence of topographic contour-based DEMs, only one study (Berthier *et al*., 2007) has estimated mass balance based on the geodetic approach. There exists a great opportunity to estimate mass balance from

DEM generation based on old topographic maps and their comparison with recent high-resolution stereo data of the Indian Himalayas. Furthermore, digital photogrammetry and airborne laser altimetry could be introduced for mass balance estimation. However, due care is required while using old topographic maps, SRTM and stereo satellite data, which need validation using GPS and DGPS survey.

This study indicates that several Himalayan glaciers are retreating at an alarming rate. Therefore, it is recommended that large-scale glacier maps and potential glacier hazard maps be prepared and updated regularly at scales of 1:5000 to 1:25,000 for the monitoring of Indian Himalayan glaciers. In addition, topographic maps of glaciated terrain should be revised in order to optimize the prevention of hazards related to glacier changes (Gilgen, 2006). A glacier information system for the Indian Himalayas, providing information about the status of glacier variability and for real-time glacier related hazards, has not yet been introduced. Contemporary efforts should, therefore, focus on the preparation of an online and integrated glacier information system for the Indian Himalayas.

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Erratum

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This article contains the following errors:

Page 691, first sentence of third paragraph should read:

In the Alaknanda basin, the ice-covered area of Satopanth Glacier diminished by 0.314 km^2 (1.5%) near the snout from 1962 to 2006, whereas Bhagirathi Kharak Glacier lost an area of 0.129 km^2 (0.4%) during a similar time period (Nainwal *et al*., 2008).

Page 685, Table 4, Rivera *et al*. (2005) observations and outcomes should read:

This study found a maximum ice thinning of 5.4 ± 0.55 m a^{-1} (. . .)

Page 686, Table 4, second sentence of Schiefer *et al*. (2007) observations and outcomes should read:

After bias correction, the thinning rate was estimated at 0.78 ± 0.19 m a^{-1} in this study

Page 691, lines 5–11 of second column should read:

Kulkarni *et al*. (2007) concluded that the number of glaciers increased between 1962 and 2001 due to disintegration of larger glacier masses. This study suggests that glaciers <1 km^2 lost 38% ($\sim$0.95%/a) of their 1962 area (. . .)

Page 691, lines 13–17 of second column should read:

Similarly, several studies outside the Himalayas such as in the Swiss Alps suggest that glaciers <1 km^2 lost 57% of their area ($\sim$2.1 %/a) during 1973 to 2000 (Zemp *et al*., 2007).

Page 692, lines 14–15 should read:

Kulkarni *et al*. (2005) estimated an average recession rate of 168 m/a for the Parbati Glacier from 1962 to 2001 (. . .)